Beyond R.G.B.: Spectrum-Based Color Imaging Technology

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Abstract

The issue of color is now receiving considerable attention in the applications of imaging technology. It is difficult to reproduce the original color of subject in conventional imaging systems, and it obstructs the applications of visual communication systems in telemedicine, electronic commerce, and digital museum. Recently, the color videos, still-images, and prints are reproduced with significantly better quality than before, but there still remain limitations imposed by RGB trichromatic system. To breakthrough the limitation of RGB 3-primary systems, "Natural Vision" system has been developed aiming at an innovative visual communication technology, which enables high-fidelity color reproduction, based on spectral information. The experimental multispectral systems for both still-image and video have been elaborated and shown following features of spectrum-based scheme; a) Highly accurate color reproduction is possible with multispectral imaging, even under different illumination environment. b) Extended color gamut can be reproduced by multiprimary color displays. c) The influence of observer metamerism, which is considered as a cause of color disagreement between different media, can be reduced by the spectral color reproduction. d) The quantitative spectral attributes of object, useful for the analysis or the recognition of object, are captured and preserved. In addition, the effectiveness of the system has been demonstrated through experiments in the application fields, such as medicine, digital archives, color printing, electronic commerce, and computer graphics.

Introduction

Digital images are widely used at present in digital broadcasting, digital still cameras (DSC's), and the image delivery through the broadband network, and are being applied to the extended fields such as telemedicine, electronic commerce, and electronic museum. The natural color reproduction is one of the key issues in these applications, as well as the high-resolution or large-screen display technologies. However, many of conventional color imaging systems are designed for user preference, and it is difficult to reproduce the original color of the object. The color management technology is greatly progressed especially in color printing, but there still remains a limitation in color reproducibility in RGB 3-primary color systems.

In this article, an approach to breakthrough this limitation, using more than three primary colors is introduced. Although there have been reported researches and developments on multispectral imaging technology [1-3], total system based on spectral information has not been established yet. Natural vision (referred as NV hereafter) is an industry-government-academy joint project aiming at the development of visual telecommunication system that enables the high-reality image reproduction with natural color [4]. The project has been performed at Akasaka Natural Vision Research Center (NVRC) from 1999 through 2006, conducted by NICT (National Institute of Information and Communications Technology, formally TAO) under the support of the Ministry of Internal Affairs and Communication. Researchers from academic institutes (Tokyo Institute of Technology and Chiba University) and industry (NTT Data, Olympus, NTT, etc.) were participated in the project. The activity of NV is currently being continued.

The research subject in NVRC includes multispectral image acquisition, compression, transmission, storage, analysis, and the color reproduction on multiprimary or 3-primary display for both video and still-images. It is also an important mission to integrate a model system to demonstrate the effectiveness of the spectrum-based technology in various fields of applications. In spite that color printing itself was out of the scope of the project, the effectiveness of the application to the printing field has been experimentally demonstrated. It is also convinced that the video and still-image applications and printing fields share the common direction in color reproduction technology.

Spectrum-based color reproduction system

Why is spectrum-based system needed?

For the natural color reproduction of real scene as if the observer were at the site as shown in fig.1(a), accurate color information needs to be captured and reproduced on a screen. However, the RGB values obtained in conventional systems often have different meanings, depending on the device characteristics. Even if the RGB signal is compliant to the CIE standard, most of the color cameras do not satisfy Luther condition, namely, RGB signal does not have one-by-one correspondence to the tristimulus values perceived by human vision. Spectral consideration is thus essential in the design of image capturing systems.

To reproduce the color as if the object were placed in the presence of the observer [fig.1(b)], the color under different illuminant is required. White balance adjustment in conventional color imaging is performed in RGB space, sometimes introducing color appearance model. But the colorimetric accuracy is not high, because spectral reflectance of object and the spectral distribution of illuminant are required for calculating the color under different illuminant, in principle. When images are displayed on softcopy monitors, it is possible to reproduce the color under different illuminant based on spectrum-based color conversion, in contrast to the hardcopy applications, where spectral printing is required to solve this problem [5].

In the color image display, the range of reproducible color, color gamut, does not cover all the existent colors. To enlarge the color gamut, the saturation of primary colors can be increased, but the gamut is still limited within a triangle. The multiprimary color approach, i.e., using more than three primary colors, was proposed for larger color gamut [6] [Fig.1(c)]. The gamut then becomes a

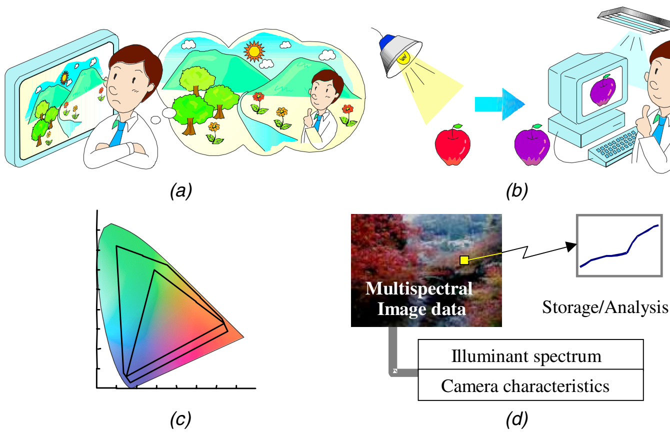

Figure 1 The role of natural vision system. (a) Reproducing the color as if the observer were at the remote site, (b) reproducing the color as if object were placed at the site of observer, (c) expanding color gamut of the display (the hexagon denotes the gamut of 6-primary projector.), and (d) enabling the storage and analysis of the image with quantitative spectral information.

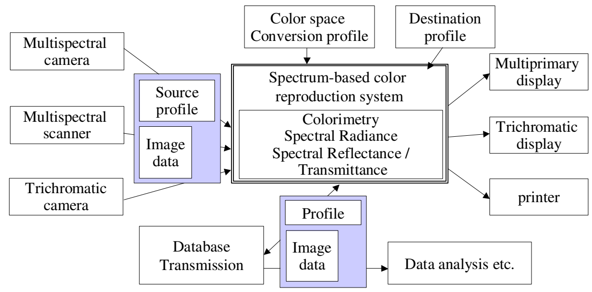

***Figure 2** The scheme of spectrum-based color reproduction*

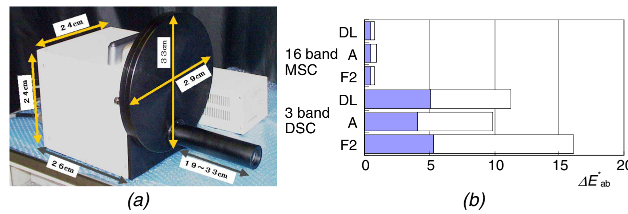

***Figure 3** (a) 16-band MSC (4M pixels/band). (b) The color estimation accuracy of 16-band MSC and 3-band DSC, under daylight (DL), CIE A and F2 illuminants, where DL was used in the image capturing.*

polygon, where its vertices correspond the color coordinates of the primaries, or polyhedron in three-dimensional color space.

In highly accurate color reproduction, the effect of observer metamerism cannot be ignored, originated by the individual difference of color matching functions. When the color displayed on a monitor is compared with the real objects, such as printed materials, the observed colors disagree each other due to the observer metamerism effect, even if the colorimetric accuracy is enough high. The multispectral and multiprimary approach solves this problem by means of spectral color reproduction.

In the digital imaging applications, image data are utilized not only for visualization, but also for the database and analysis. The original attribute of object that generates color, i.e., spectral radiance, reflectance or transmittance information, is captured and preserved with multispectral imaging [Fig.1(d)]. The quantitative color information is useful for the analysis or the recognition of object in the image database of the digital archives of cultural heritage, artworks, and clinical cases in medicine.

How does spectrum-based system work?

The concept of the spectrum-based color reproduction system is depicted in fig.2. To obtain sufficient information, multispectral camera (MSC) is desired as an input device. The profile of the input device including the spectral sensitivity, tone curve, and dark current level of the camera, and the spectral energy distribution of illuminant are attached to multispectral image (MSI) data. In image processing, transmission, and storage, the image is accompanied with the profile data, so that the spectral radiance, reflectance or transmittance can be retrieved. In image display, the image of tristimulus values or spectral radiance is reproduced on 3-primary or multiprimary color display with device calibration. The system can also provide data to color printing system in the form of CIE XYZ tristimulus values or the spectral reflectance.

The architecture of spectrum-based color reproduction system is similar to the ICC (International Color Consortium) color management system, but the profile connection space (PCS) is based on physical model, i.e., spectrum-based PCS (SPCS) instead of color appearance model. This can be any of CIEXYZ under arbitrary illumination, spectral radiance, or spectral reflectance. The information required for the transform to SPCS is held in the profile data. The profile data format was defined as NV image data format, which was proposed to CIE TC8-07. The XML version NV format was also developed for easier handling.

In this system, the numbers of channels in the image capture and the display are independent, and the input and output devices with the arbitrary numbers of channels can be employed. Three-channel devices can also be used in this system with proper device characterization, even though there arise restrictions in the color reproduction capability or accuracy.

Multispectral and Multiprimary Technology

Multispectral image capture

Fig.3(a) shows the 16-band MSC with a rotating filter wheel, developed in NVRC. The color reproducibility evaluated using GretagMacbeth Color Checker is shown in fig.3(b). The accuracy by MSC is high and smaller than the discriminable level of human vision, while visually apparent error is observed in 3-band DSC.

Fig.4 shows a 6-band HDTV camera for the acquisition of motion picture [7]. The camera was employed for the experiment of real-time video reproduction described below.

In image capturing, the spectral distribution of illumination light is also measured to estimate the spectral reflectance or the transmittance of the object. For example, the reflected light from standard white is measured by a spectroradiometer or the MSC, or the ambient illumination is directly measured by a compact fiber-optic spectrophotometer. In fact, more easy-to-handle device is expected for the measurement of illumination spectrum.

Spectrum estimation

In the spectrum-based color reproduction system, the spectral radiance, reflectance or transmittance is estimated from the MSI data. Arbitrary estimation method can be used in this system, as the original MSI data can be preserved with the spectral sensitivity

Figure 4 *6-band HDTV camera*

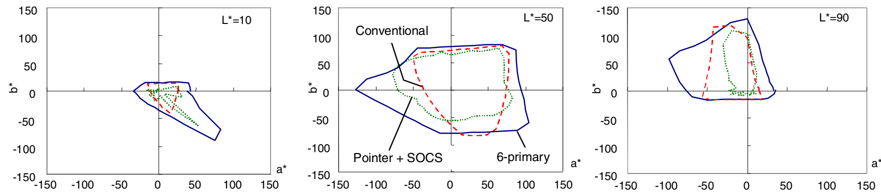

Figure 6 *Color gamut of 6-primary DLP display, conventional 3-primary DLP display, and natural object, in a*-b* planes of L* = 10, 50, and 90.*

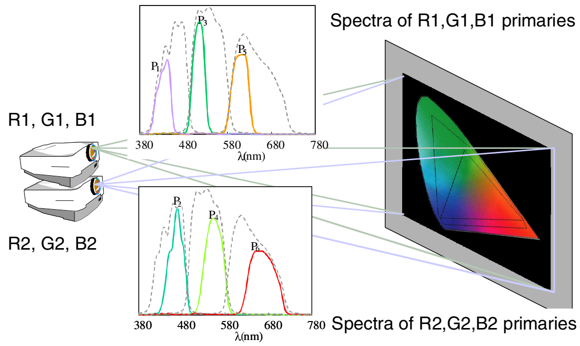

Figure 5 *The 6-primary projection display using two modified projectors. The spectral intensities of each projector are also shown.*

of MSC. Among the methods previously reported, the method based on Wiener estimation is practical and accurate. If the covariance function of spectral reflectance of target object is available, it considerably improves the accuracy. However, it is not necessarily possible to obtain the covariance function, and we can alternatively use an approximation in which the covariance is modeled as a first-order Markov process. This model works well for most natural objects, because the spectral reflectance of natural object is mostly smooth except for special cases.

Multiprimary display system

Although there were few previous works on multiprimary color displays for larger color gamut [8], the system development and evaluation of muliprimary display had been originally started by NV project. In the multiprimary projection display developed in NV, the images from two projectors (LCD or DLP), each of which is adapted to produce different 3-primary colors, are overlaid on the screen [Fig.5] [6]. As a flat-panel type multiprimary display, a 4-primary flat-panel LCD with LED backlight was implemented by means of time sequential display.

Fig.6 shows the color gamut of 6-primary DLP display [9]. As for the gamut of natural objects, Pointer gamut [10] and SOCS spectral database (except for fluorescent object) [11] are combined (Pointer + SOCS), because some objects in SOCS are out of the Pointer gamut. Six-primary DLP display almost covers the gamut of natural objects and the gamut volume in CIELAB space is about 1.8times larger than the normal RGB DLP projector. The gamut of 6-primary display is enlarged in the dark red, cyan, purple regions and bright orange, as compared with conventional RGB display.

Spectral color display

There exists variability in color matching functions of human observers; originated from the macular pigments, lens absorption, and cone sensitivity. Due to the individual difference of color matching functions, the color difference may appear to a certain observer when two color stimuli are shown, even if perceived as the same color by another observer, or CIE standard observer, called observer metamerism. It causes the color mismatch between different media, such as color printed materials and displays, even though the colorimetric match is achieved for CIE XYZ values.

Based on the multispectral and multiprimary technology, spectral color display becomes possible, and the color mismatch between the display and the real object can be disappeared for different observers. The advantage of spectral color display was experimentally demonstrated using 6-primary display [12] with the signal processing method briefly explained in the next subsection.

Multiprimary color conversion

The multiprimary color signal is generated from the image of tristimulus values or multispectral data, called multiprimary color conversion, similar to the color decomposition for multiprimary color printers. For colorimetric color reproduction, 3-dimensional tristimulus values are transformed to M-dimensional multiprimary color values. It involves a degree of freedom; plural combinations of multiprimary color values can reproduce a certain color. Several methods have been developed for 3to$M$ color conversion [13,14]. The computation speed, the easiness of hardware implementation, and the image quality depend on the conversion method.

For the spectral color reproduction explained in the previous subsection, it becomes $N$to$M$ conversion, where N is the number of channels of MSI. In the proposed $N$to$M$ conversion method, the spectral error is minimized under the constraint that the colorimetric match is attained for the standard observer, and its effectiveness was experimentally confirmed [12].

When an image with smooth color tonal change is reproduced on a multiprimary color display, a contour-like pattern sometimes appears. The observer dependence of color matching function and the device characterization error are the sources of the artifact, and proper selection of multiprimary color conversion suppress such artifact [14]. Color tone reproducibility is one of the important issues for image quality in mutiprimary displays.

Multispectral image transmission, compression

The system architecture of image transmission and signal processing in spectrum-based color reproduction system is shown in fig.7. The same scheme can be used in the storage of image data. There can be considered three cases for implementation.

The prototype of the multispectral video transmission was also developed. By using multiprimary color conversion hardware, real-time colorimetric reproduction is realized with 6-band MSC and 6-primary display in HDTV resolution [4].

The compression and encoding are the other issues on MSI transmission. As an MSI compression technique considering the colorimetric accuracy, modified KL transform called weighted KL transform was proposed and combined with JPEG2000 scheme [16].

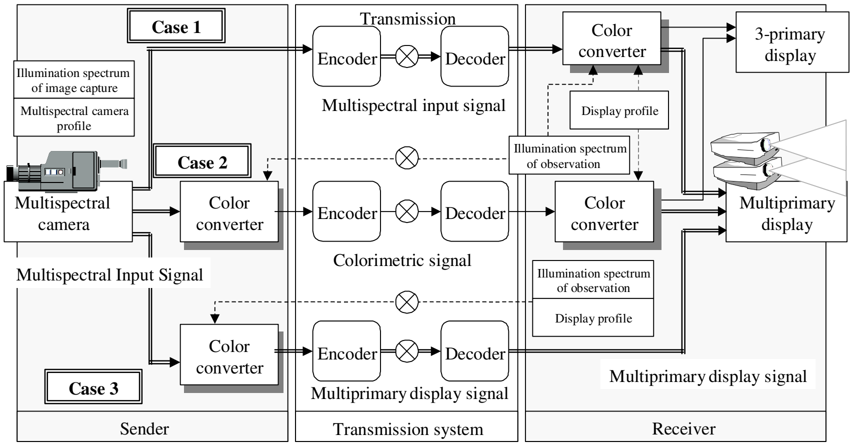

Figure 7 *The system architecture of multispectral video transmission.*
Case 1 Multispectral input signal is transmitted, and the color under the arbitrary illuminant can be computed at the receiver site. This scheme is suitable for image archive and distribution purposes.
Case 2 The spectrum of observation illuminant is passed to the sender in advance and the color under the observation illuminant is transmitted. Suitable for one-to-one communication, or natural color reproduction with fixed observation illuminant.
Case 3 The spectrum of observation illuminant and the display profile are passed to the sender in advance, and the display signal is transmitted. This seems suitable for client-server image transmission

For video compression, several methods that support multichannel images were tested, including a coding method in which MSI signal is converted into visible and invisible components, considering the compatibility to the conventional video signal.

JPEG2000 is one of the suitable formats for high-quality encoding of both video and still MSI's. The profile data for NV format described above can be easily implemented in JPEG2000 as a extended ICC profile or metadata with using XML.

Multispectral image analysis and database

MSI can be considered as a value-added color image, because every pixel has quantitative spectral data. Thus it is possible to make use of MSI data with the image database and analysis. We have developed several techniques for image processing, analysis, and retrieval that utilize spectral data. Those techniques are developed for specific applications explained in the next section, but they can be applied to other applications as well.

Applications

Medical application

The use of digital color images is extremely valuable for tele-conference, teleconsultation, education, training, image analysis, and reference database, in pathology, endoscopy, and dermatology. It is also required to reproduce the complexion of a patient through visual communication system for the telediagnosis and homecare. If the reproduced color is not accurate, it may cause misdiagnosis, thus the reliability of reproduced color is critical.

In the pathology application, the spectrum-based system enables not only the accurate color reproduction of stained tissue sample, but also the correction of variation in staining condition, with adjusting the amount of stain through digital process. In dermatology, MSI systems of both still-image and video were tested and the color reproducibility of multispectral system was shown to be sufficiently high. from the visual evaluation by dermatologists. It was also shown that spectral information can be also utilized for the image analysis that supports diagnosis in both pathology and dermatology, for example, the grading of disorders or the quantitative evaluation of treatments [16].

Digital archive and electronic museum

The color of the archive depends on the imaging device and illumination condition if we use conventional imaging devices. There have been many reports on the multispectral imaging for digital archive. The result of color reproduction on a display using 16-band multispectral image was shown to be satisfactory for the art management staffs in NV project. The image data can be also employed for the high-fidelity color prints as explained in the next subsection. The spectral information in the image will be useful for the analysis of pigments or dyes, or the selection of material for restoration. In the capturing of historical works, it is often necessary to minimize light irradiation, so flush light synchronized with 16 exposures was used in the experiment.

Printing Application

Although printing technology is not a subject of this project, it has been proved that multispectral imaging greatly improves the fidelity of color prints. As a test for the printing of catalogs for product promotion, assuming normal photographing situation of commercial products, a 16-band MSC and professional RGB DSC's were compared. In the multispectral image capture, flush lamps were synchronized with shutters for 16 times exposures. From the image captured by MSC and the spectrum-based color reproduction, the image in CIEXYZ color space under standard D50 illuminant was calculated. Then it was printed by an inkjet printer with using ICC profile prepared for this purpose. From the printed images obtained from the RGB DSC, which is used in the normal color proofing, a professional print director put 4-5 instructions for color corrections on average per printed sample. On the other hand, no instruction for color correction was given to any of resultant samples from 16-band MSI. The print director also commented that the printed results from MSI is even better than the proof produced from RGB DSC after the color correction [17].

The technique was also applied to the print of artwork replicas in collaboration with Aomori Digital Archives Association. Conventional color management technique was applied in printing process, and the color is almost identical to the original.

Furthermore, the spectral color display can be useful for the color proofing applications using softcopy monitors, since the color matching between display and print is considerably improved thanks to the spectral approximation.

Electronic commerce application

In the electronic commerce (EC) for BtoC such as the online-shopping with using color images, the color difference causes the return of purchased items. In BtoB EC, the color matching of samples between designers, factory, buyers, and sales is needed and the quantitative color information is quite beneficial. The display of wider color gamut is also required in textile applications. High-fidelity natural color reproduction system will contribute the further progress in EC of vehicles, apparels, cosmetics, toys, and interior furnishings. A web-based server-client prototype of electronic catalog system was developed in NV.

Digital prototyping - spectral BRDF measurement and rendering

Digital prototyping is an important technology for expedition and efficiency of product development, and CG enables the realistic rendering of virtual products, using Bidirectional Reflectance Distribution Function (BRDF) or Bidirectional Texture Function (BTF), but the color disagrees with real products. The multispectral BRDF/BTF measurement system and multispectral rendering technique were developed for high-fidelity color digital prototyping.

Conclusion

The concept, technology, and applications of spectrum-based color reproduction system are introduced in this paper. It enables not only the high-fidelity color reproduction but also the application of image analysis based on the quantitative spectral information. Moreover, multispectral information will be also of great utility in the image editing for preferable color, and other various image processing such as object extraction or image synthesis, though those were not the main topic of NV project that basically aims to natural color reproduction.

Wide gamut display is one of the recent topics in display industry, and the presentations of multiprimary displays can be also found from other groups. But conventional color cameras devices and image color spaces such as sRGB does not support wider gamut image data presently.

Going beyond RGB, great benefit emerges in advanced imaging applications. Multiprimary printing is already available in commercial product, but to make better use of devices that support innovative color reproducibility, a platform for spectrum-based system is expected, i.e., multispectral and wide-gamut video contents creation, management, distribution, and utilization.

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